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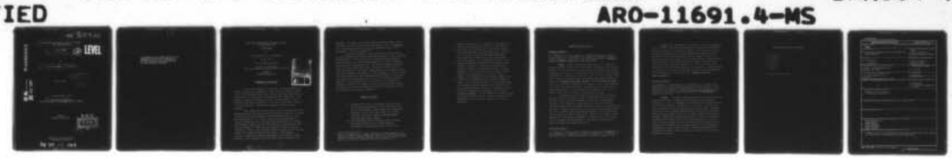

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FAST FRACTURE RESISTANCE OF GLASSY POLYMERS
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FINAL REPORT

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M. F. Kanninen and A. R. Rosenfield

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STATEMENT OF THE PROBLEM

The ultimate strength of all materials is connected with their ability to resist crack propagation. Fiber reinforced polymers, because of their light weight and their high corrosion and fatigue resistance, are highly useful for a wide range of military and other applications. Consequently, quantitative predictions of the fracture strength of these materials under service conditions -- particularly under impact loading -- is of some importance. However, such procedures have not yet been developed.

Fiber composites offer much higher fracture resistance for crack propagation across the fibers than does an unreinforced matrix. The reason is simply that the energy required for fiber breakage, pull-out, fiber/matrix debonding, etc. is so high. However, because composites can fracture in other ways (e.g. by matrix splitting parallel to the fibers), this apparently enhanced fracture resistance may not represent the actual fracture strength of a fiber reinforced composite material in service conditions. Clearly, a basic fracture predictive capability that can take account of the various different ways in which a fiber composite can fail is required for realistic assessments of the behavior of these materials. Such a capability will also enable their performance to be

optimized. For example, recent work on fiber reinforced kinetic energy projectiles shows that their enhanced performance is due to a combination of (1) high failure resistance in the axial direction, and (2) low resistance to shear crack propagation.*

This work is addressed to the determination of the resistance to a fast running crack initiated under impact loading in a fiber reinforced polymer material. The work is based on a dynamic fracture mechanics approach developed on a previous Army Research Office Grant (P-9538-MC) which focused on high-strength steel. This approach produced controlled crack initiation using static loading of blunt-notch double-cantilever beam (DCB) specimens. The present program applies this procedure to fiber-reinforced composites and extends it to impact loading. The major objective is to develop dynamic fracture mechanics procedures capable to describing crack initiation, propagation, and arrest in fiber reinforced composite materials. The second objective of the research is to elucidate the principles involved in the dynamic fracture of fiber-composites, thereby providing a basis for both optimizing the design of these materials and for evaluating actual military components.

SUMMARY OF RESULTS

(1) The mathematical model for the double cantilever beam fracture specimen developed for steel under static loading has been extended to treat dynamic crack propagation and arrest in fiber reinforced polymers by including orthotropic constitutive behavior and crack growth initiation under impact loading.

(2) Low-volume-fraction wire-reinforced polymer composites have been developed for use as model materials. Measurements of the individual matrix fracture, wire

*See M. F. Kanninen and G. T. Hahn, "Strategy for Future Research on the Analysis of Kinetic Energy Penetration", Battelle's Columbus Laboratories Report to the Defence Advanced Research Projects Agency, January 31, 1978, which was based in part on results obtained in this project.

fracture, and wire pull-out components of the propagating crack fracture energy have been made for this material.

(3) A drop tower was constructed to produce impact loading on notched DCB specimens. The tower, which has a capacity of 135 J, was used to measure crack velocity and crack arrest behavior as a function of wire packing density and of wire geometry (i.e. longitudinal versus cross-ply).

(4) Comparisons between the predicted and the observed crack arresting capability of wire-reinforced polymers have been made by means of the mathematical models. Of most importance, it has been learned that the dynamic fracture toughness of the composite is not equal to a single summation of the energies in the individual failure events.

(5) A direct way of determining dynamic fracture toughness values (i.e. by forcing the model to follow the experimental crack length-time record) was devised for comparison with the conventional indirect method (i.e. performing computations with assumed fracture toughness values to match experimental results). It was learned that the effectiveness of the direct method calls for a degree of precision in the experiment that is not readily obtainable with current techniques.

SUMMARIES OF PUBLICATIONS

Publication Number 1

M. F. Kanninen, "A Critical Appraisal of Solution Techniques in Dynamic Fracture Mechanics", Proceedings of the Conference on Numerical Methods in Fracture Mechanics, A. R. Luxmoore, and D.R.J. Owen, editors, University College of Swansea, Swansea, U.K., 1977, pp 612-633.

Summary. Dynamic fracture mechanics consists of all fracture mechanics problems in which inertia forces must be included in the equations of motion for the cracked body. A logical way of classifying the problems addressed in the subject is in terms of the initial/boundary conditions that are appropriate. The bulk of current work is on one of two distinct problem types. These are the initiation of crack growth under impact loading and rapid crack propagation under fixed loading. (It is now clear that crack arrest is not a separate category but is properly treated as the termination of a dynamic crack growth analysis.) The principle aim of this paper is to assess the usefulness of various numerical techniques in terms of their appropriateness for the solution of these physical problems.

Mathematically, while closed form solutions can be obtained in some specialized cases, most solutions in dynamic fracture mechanics are obtained by either the finite difference or the finite element method. Currently, finite elements are better suited for initiation of growth calculations while finite differences can better cope with crack propagation and arrest. Emphasis in the paper is also put upon the use of simple models which can circumvent large-scale numerical analyses by exploiting the geometric conditions in special applications. Finally, it is pointed out that extensions of linear elastic treatments -- which form the bulk of current efforts in dynamic fracture mechanics -- are needed to treat elastic-plastic and viscoelastic material behavior.

Publication Number 2

P. C. Gehlen, C. Popelar, and M. F. Kanninen, "Dynamic Crack Propagation in the DCB Specimen: A Comparison of Theory and Experiment", accepted for publication in the International Journal of Fracture, to appear in 1978.

Summary. The formulation of the problem of a rapidly propagating crack in a double cantilever beam specimen is re-examined using Reissner's variational principle. The governing equations are first solved to obtain the static compliance which is in good agreement with measured values. The equations of motion in conjunction with the energy criterion for a running crack are solved using a finite difference method. Predicted crack growth versus time, crack speed versus crack length, and dynamic stress intensity factors versus crack length are all found to be in very good agreement with their measured counterparts for a polymer. Of most importance for future work, it is found that the most effective one-dimensional model for the DCB specimen is a combination of a Timeshenko beam and a Winkler foundation.

Publication Number 3

M. F. Kanninen, A. R. Rosenfield, P. M. McGuire and C. R. Barnes, "The Determination of Dynamic Fracture Toughness Values and Evaluation of Crack Arrester Concepets Using the DCB Test Specimen" (in preparation), to be presented at the symposium on Crack Arrest Methodology and Applications, November 6-7, 1978, Philadelphia, and published in an ASTM Special Technical Publication.

Summary. The double cantilever beam (DCB) test specimen is well-suited for the study of dynamic crack propagation and arrest events. Experimentally, rapid crack growth can be initiated and arrested within the confines of the specimen. In addition, it is possible to analyze these events through the use of a relatively simple analysis model. This paper describes the use of combined experimentation and analysis to determine dynamic fracture toughness values for a polymeric material using the DCB specimen. Comparisons are made between results obtained by crack growth initiation from a blunted crack and from impacting loading of a sharp crack. Particular emphasis is put on the difficulties involved in direct computation of toughness values through simulation of the experimentally determined crack growth versus time data. Some computational results illustrating the basic concepts involved in the design of crack arrester systems are also given.

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No advanced degrees awarded.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A summary is given of experiments and analysis involving rapid crack propagation and arrest in wire-reinforced polymer composites.

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